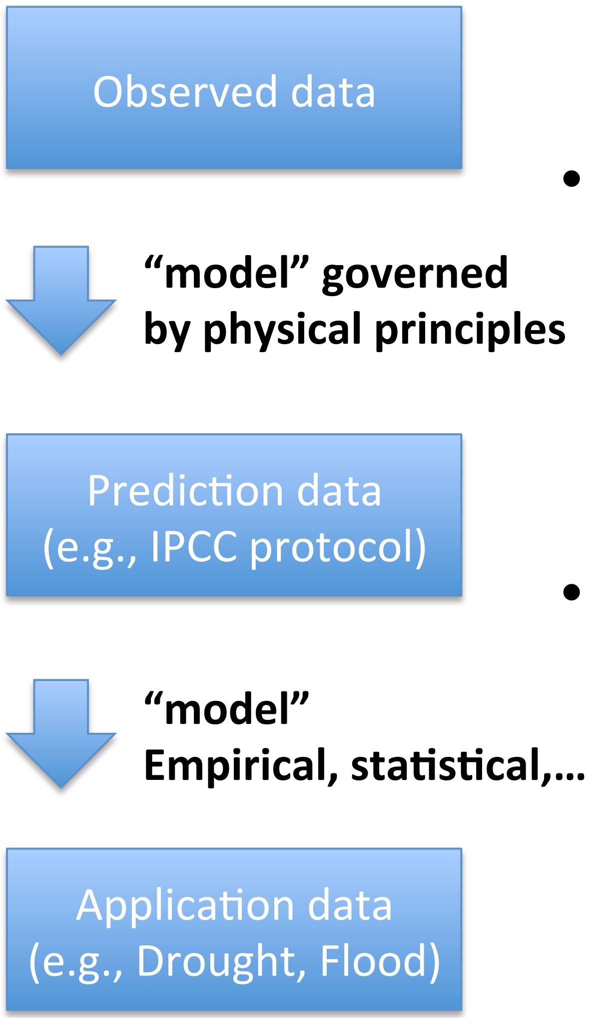
Toward quantifying and reducing uncertainty in climate prediction

Takashi Mochizuki
(Japan Agency for Marine-Earth Sci. and Tech.; JAMSTEC)

気候予測における不確実性の定量化・低減化

望月　崇
（独立行政法人海洋研究開発機構）

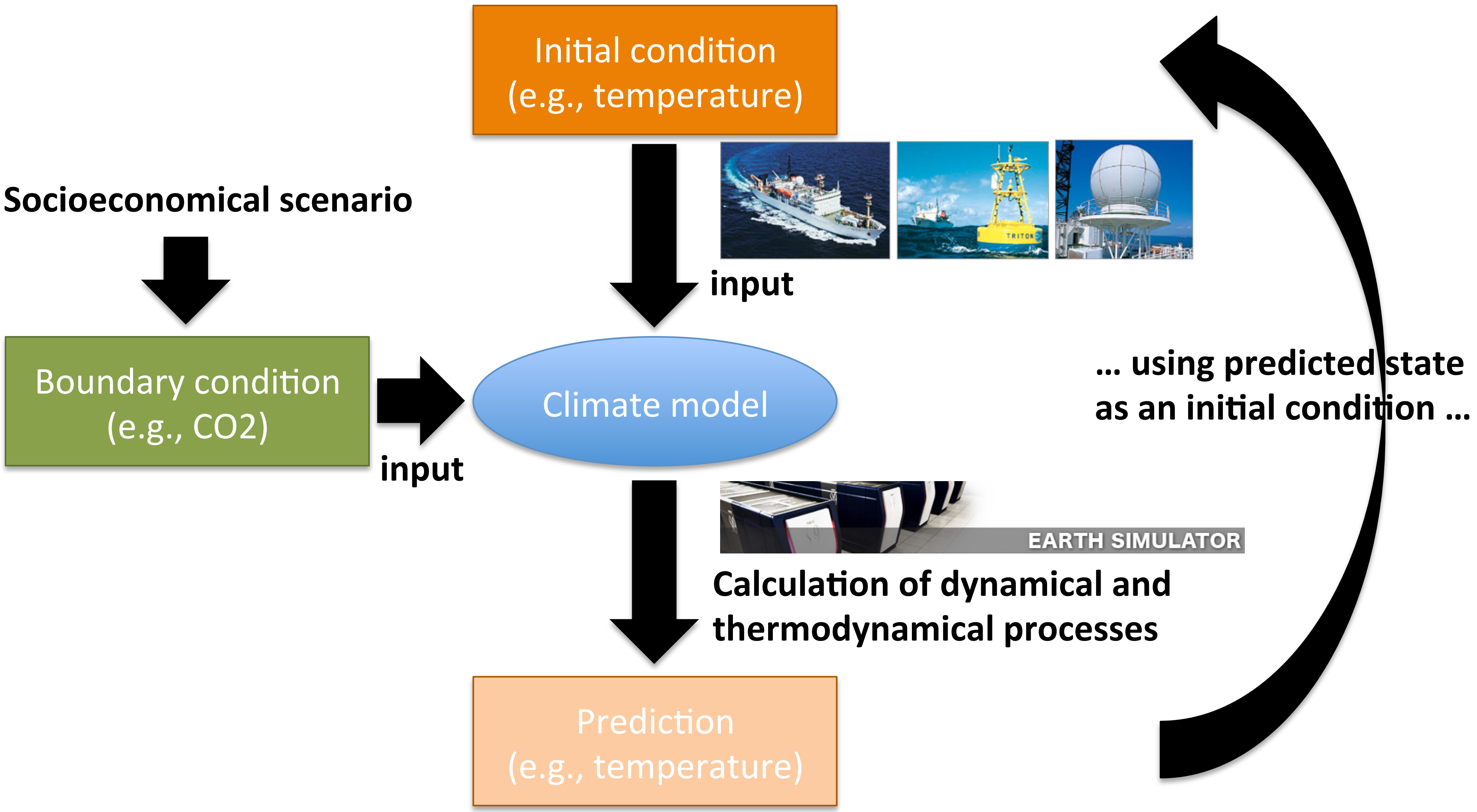
Approaches toward better climate "prediction"



- Climate prediction community
  - To obtain **prediction data** with quantifying and reducing errors and uncertainty.
  - Optimization and calculation **with keeping general principles** in climate model.

- Climate informatics community
  - To extract meaningful information from huge amounts of observed and/or **predicted data.**
  - Optimization and/or model development **even if breaking general principles** of dynamics and thermodynamics in "model."

How to perform climate prediction…



Climate prediction is basically deterministic.

Sources of errors and uncertainty

- **Climate model (all timescales)**
  - Simultaneous partial differential equations for geo-fluid dynamics and thermodynamics
    - Governed by general principles (i.e., not empirical)
    - Basically **deterministic** prediction

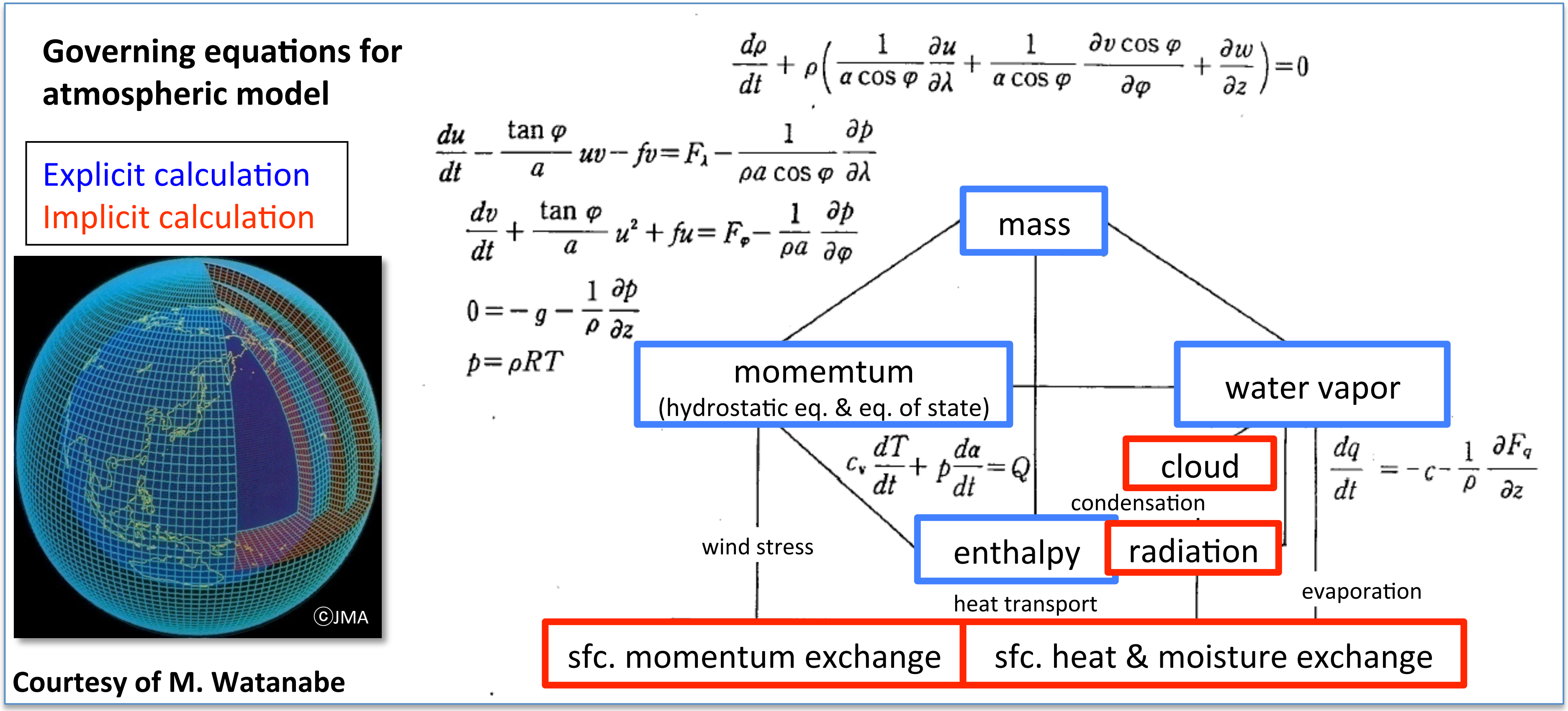
- **Initial condition (…, day, week, season, year, decade)**
  - Climate state at initial time of prediction experiments (e.g., observations)
    - Not always, not everywhere, not every variable
    - Not satisfying general principles

- **Boundary condition (decade, century,…)**
  - Concentration of CO2, …
    - Based on socioeconomical scenario => not limited into geoscience

Climate model

(weather forecasting, …, global warming simulations)

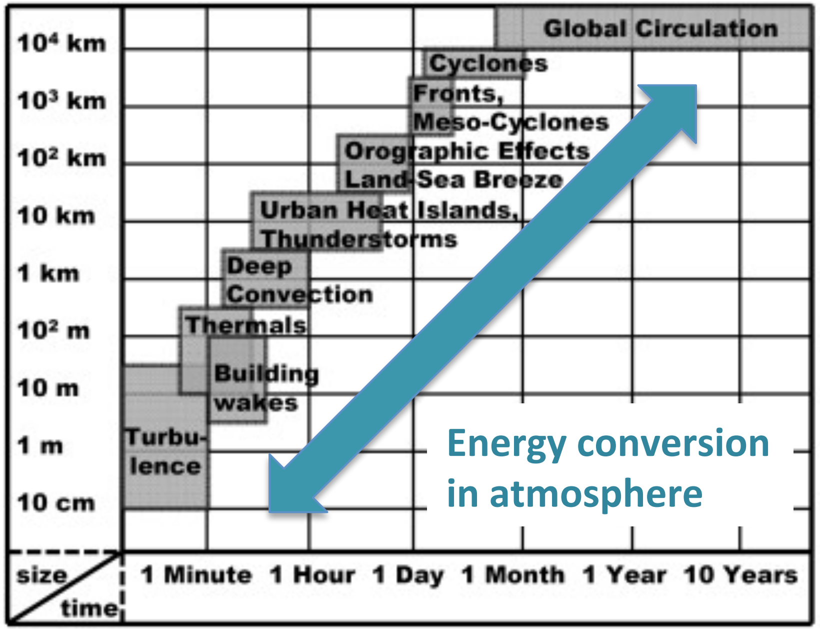
- Simultaneous partial differential equations govern climate processes in atmosphere and ocean (i.e., basically **deterministic**).
- **Probabilistic / stochastic** approximation is not needed, if we can represent (i.e., climate model can resolve) all processes explicitly.



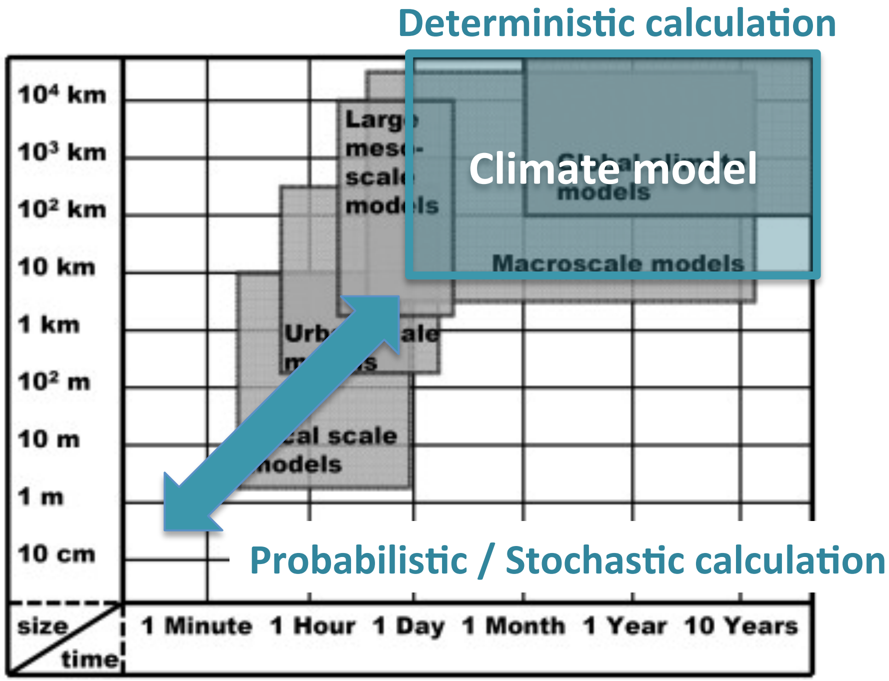
Climate model

(weather forecasting, …, global warming simulations)

- In a practical sense, we need implicit (i.e., **probabilistic / stochastic**) calculations to take into account contributions from small/short timescale phenomena.
  - Atmosphere-ocean interaction
  - Wave-mean flow (small-scale and large-scale) interaction
  - Parameterizations for cloud, radiation, …



Spatiotemporal scales of atmospheric phenomena

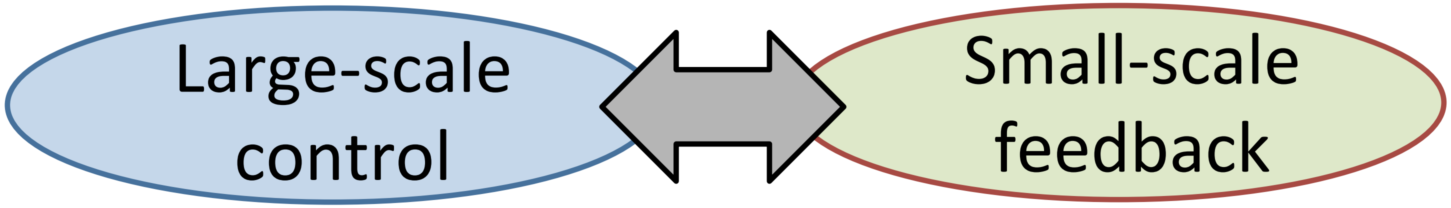


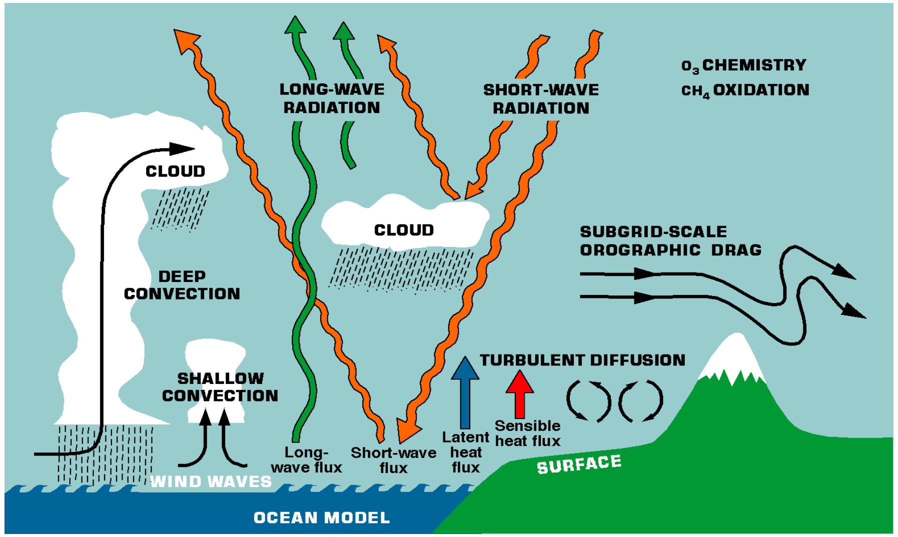
Spatiotemporal scales covered by atmospheric models

Isaksen et al. (2009)

Climate model cannot explicitly cover all spatiotemporal-scale phenomena.

Parameterization Issues





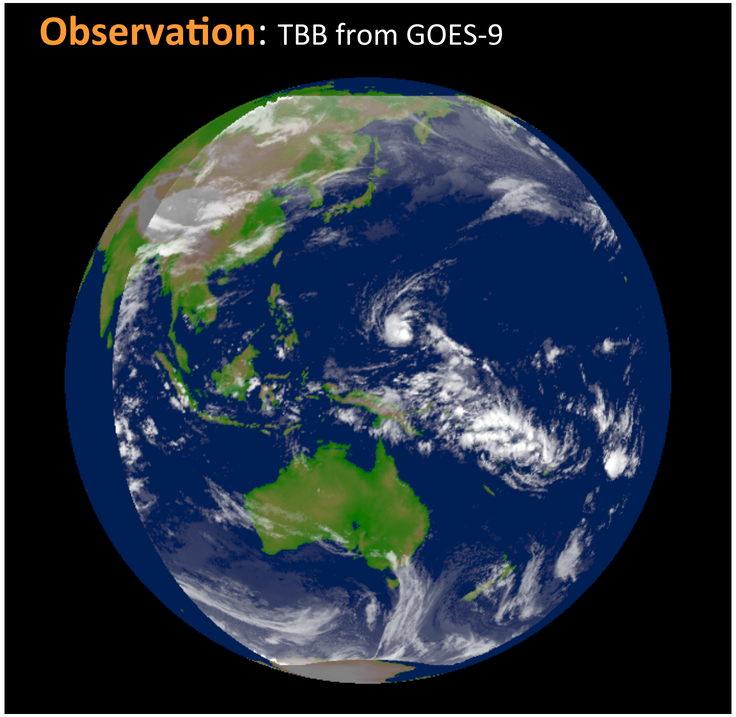
Beljaars (2004)

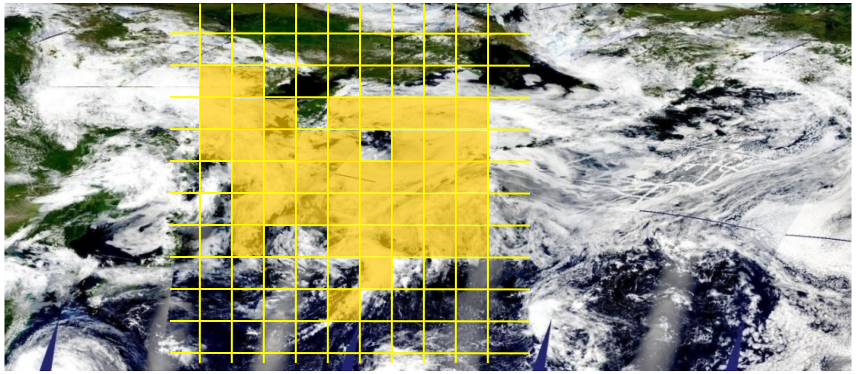
- We do not *explicitly* calculate small-scale phenomena (e.g., *individual cloud).*
- We do *implicitly* calculate *effects* of small-scale phenomena on large-scale phenomena (e.g., *heating/cooling by cloud formation, solar radiation changes by clouds*).

Parameterization of small-scale (unresolved) effects by using large-scale (resolved) variables.

Probabilistic parameterization (current approach)

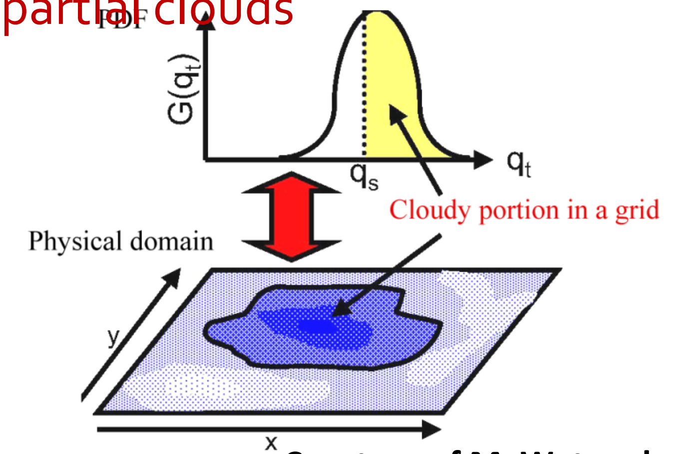
Clouds are important elements of climate, but highly inhomogeneous…





"All or nothing" cloud is too crude for model !

Assumption of a probability distribution of the sub-grid scale moist fields to represent contribution of partial clouds



Parameterization ≠ empirical rule

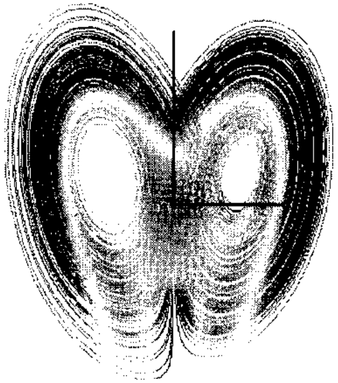
≠ strictly based on small-scale physics

But it needs assumptions, leading to a variety of the scheme.

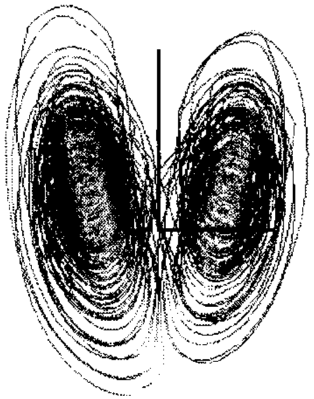
Courtesy of M. Watanabe

Stochastic parameterization / physics (challenging issue)

Lorenz's attractor



Third axis replaced
with additive noise



Palmer (2001)

Approach:
Adding random noise (artificial term)
to time tendency of physical processes
(e.g., Stochastic fluctuation from quasi-equilibrium)

Parameters:
Amplitudes of random noise
Time scales of noise (auto-correlation in time)
Spatial scales of noise (auto-correlation in space)

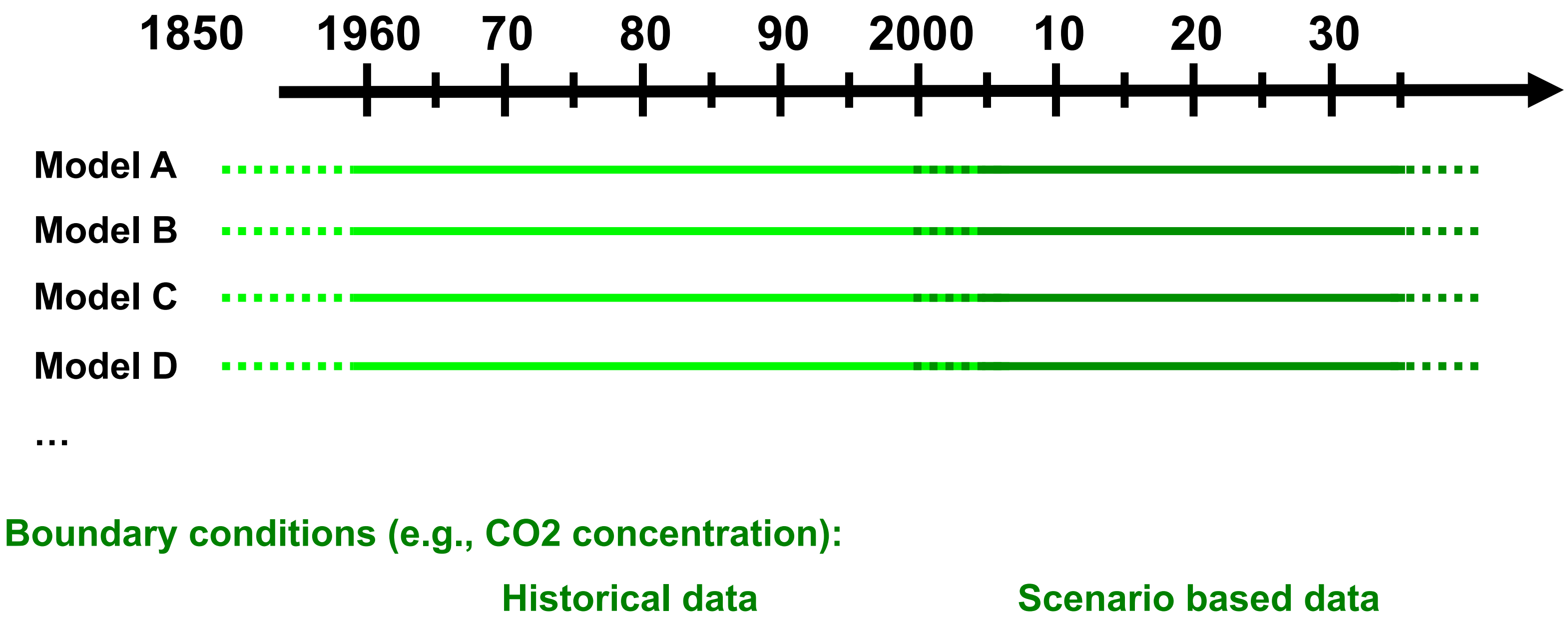
Benefits:
Better estimate of uncertainty
(e.g., Enhanced spread, Reduced bias and errors…)

But… difficulty in numerical reproducibility

Buizza et al. (1999)
Palmer (2009)
Palmer & Williams (2012)

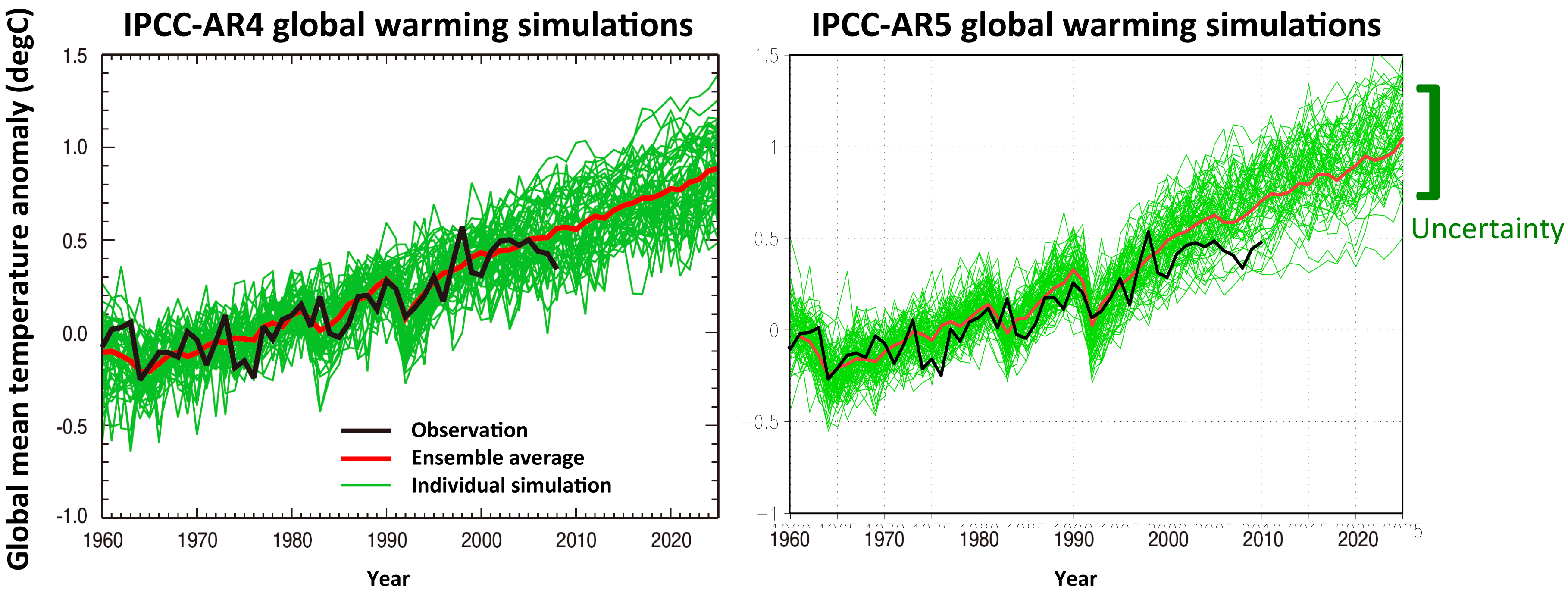
Estimate of uncertainty (Current approach)

- Rather than stochastic parameterization / physics, we use simpler **ensemble approach** to estimate uncertainty due to probabilistic / stochastic approximation.
  - Models with different parameterizations (≠ values of parameters)
  - Models with different initial conditions



Estimate of uncertainty (Current approach)

- Instead of stochastic parameterization / physics, we use **ensemble approach** to estimate uncertainty due to probabilistic / stochastic approximation .
  - Models with different parameterizations (≠ values of parameters)
  - Models with different initial conditions



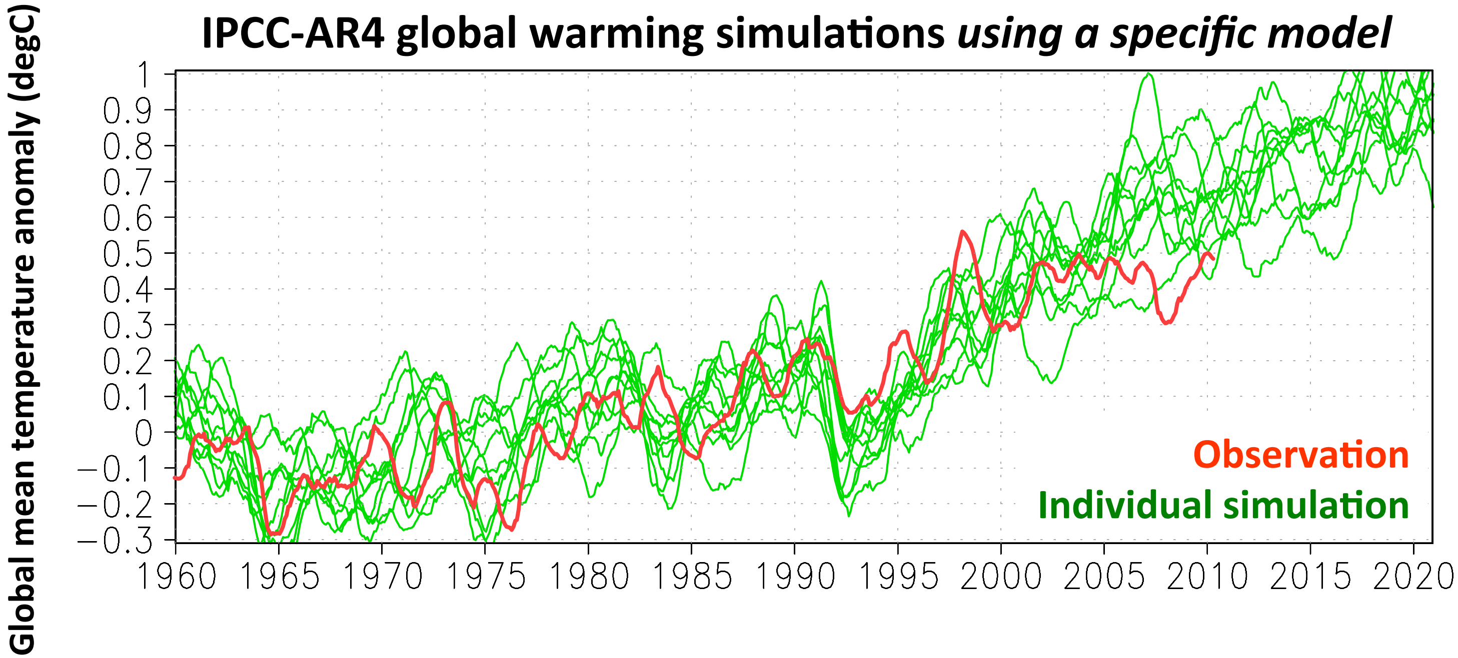
Sources of errors and uncertainty

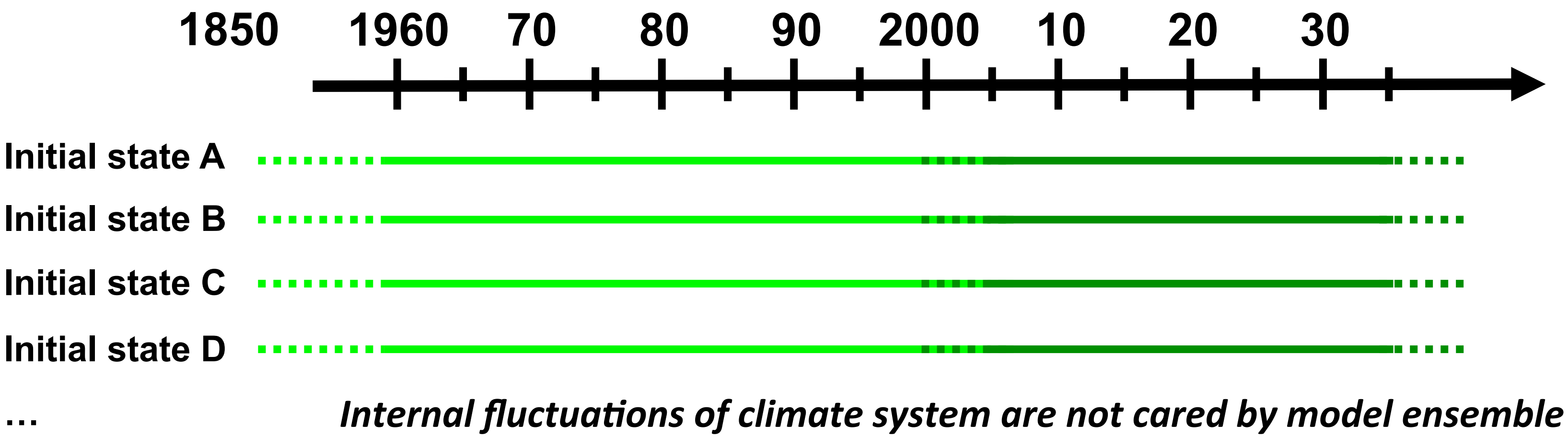
- **Climate model (all timescales)**
  - Simultaneous partial differential equations for geo-fluid dynamics and thermodynamics
    - Governed by general principles (i.e., not empirical)
    - Basically **deterministic** prediction

- **Initial condition (…, day, week, season, year, decade)**
  - Climate state at initial time of prediction experiments (e.g., observations)
    - Not always, not everywhere, not every variable
    - Not satisfying general principles

- **Boundary condition (decade, century,…)**
  - Concentration of CO_2, …
    - Based on socioeconomical scenario => not limited into geoscience

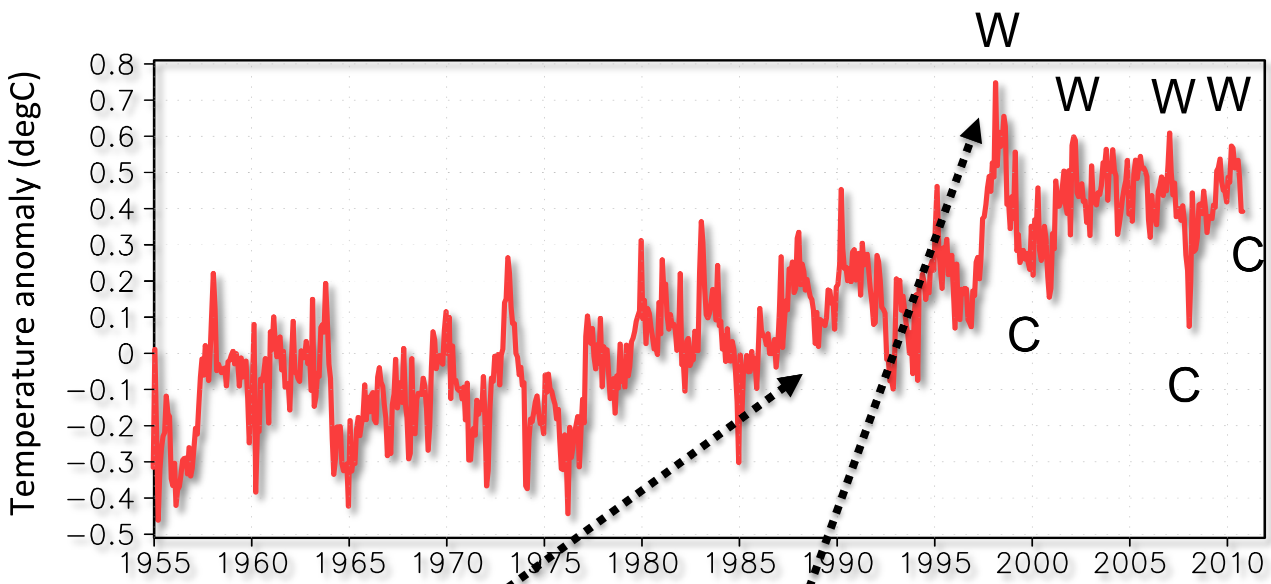
Uncertainty realized by initial conditions
(New topic in IPCC-AR5)

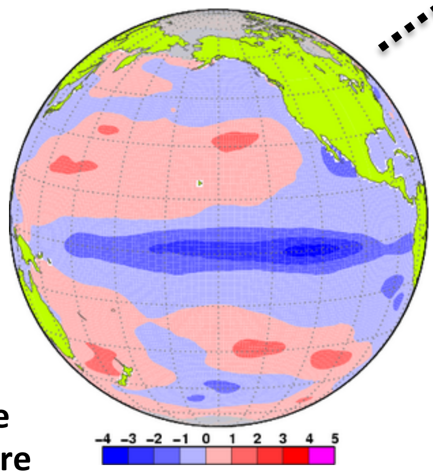




Internal fluctuations of climate system are not cared by model ensemble approach.

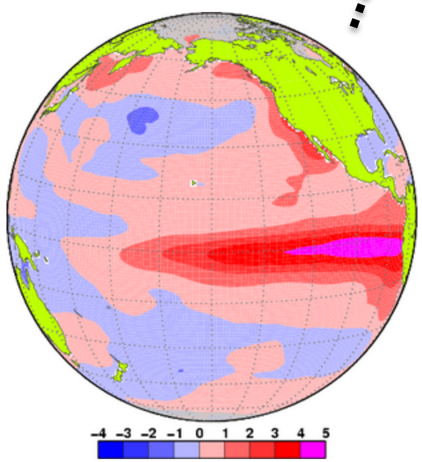
Fluctuations on interannual (1-2years) timescales



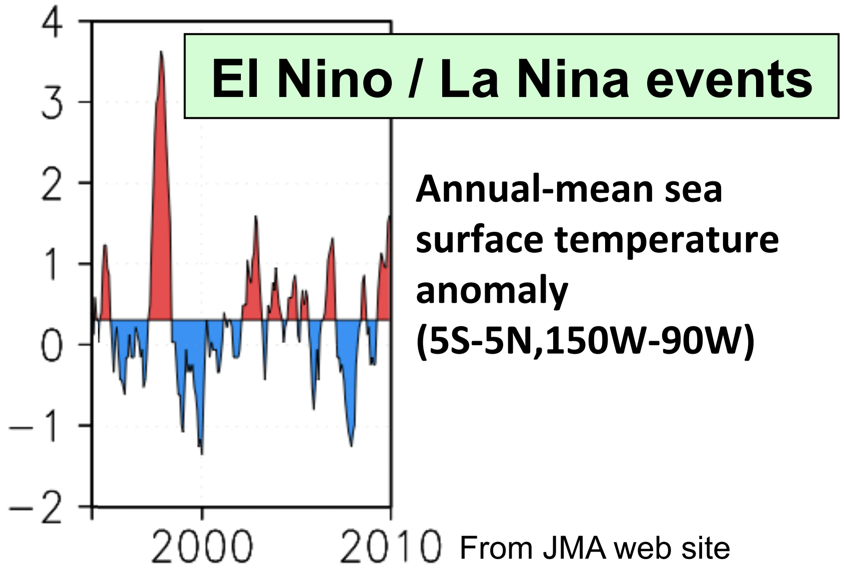


Sea surface temperature anomalies

December 1988



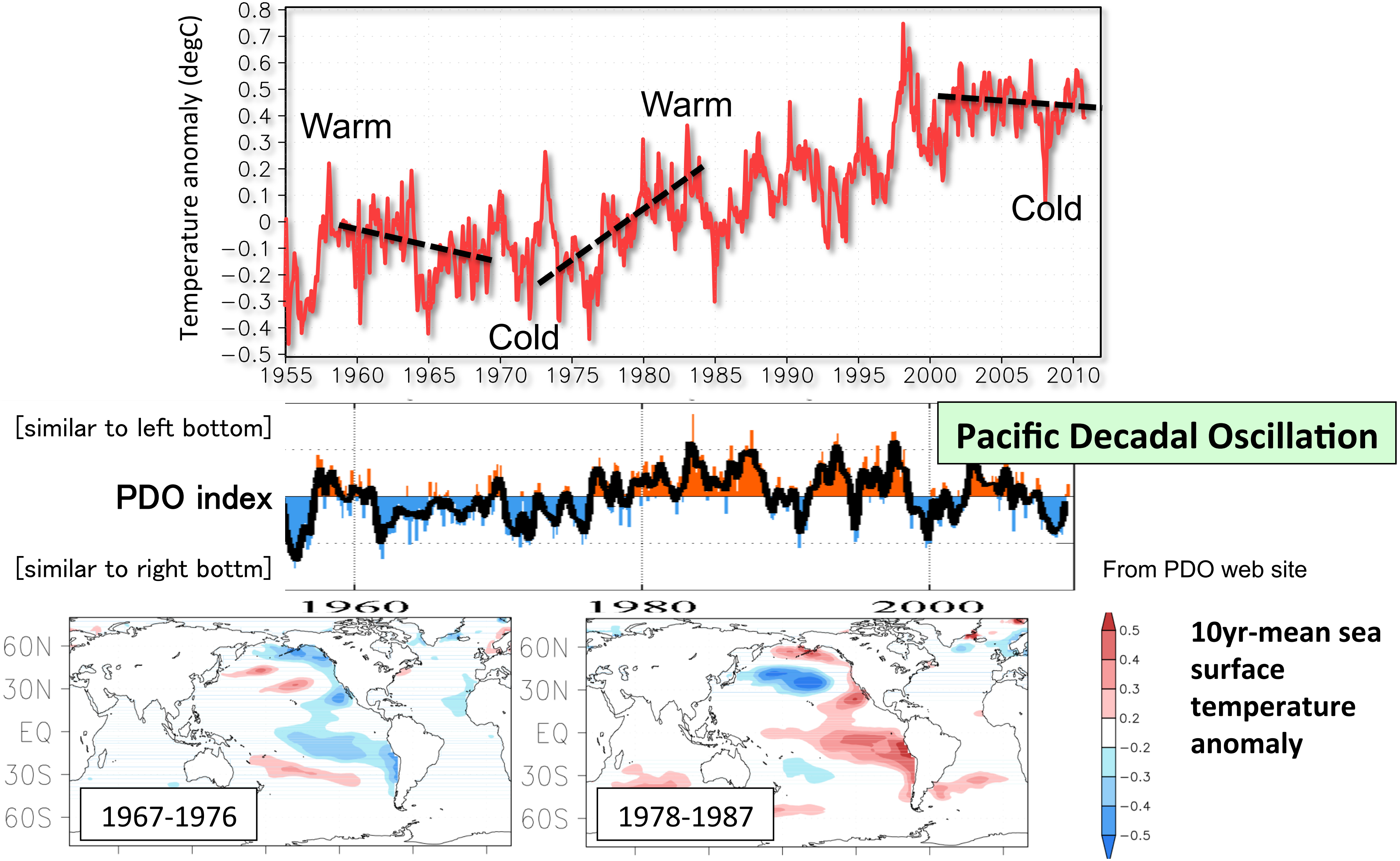
November 1997



Annual-mean sea surface temperature anomaly (5S-5N,150W-90W)

From JMA web site

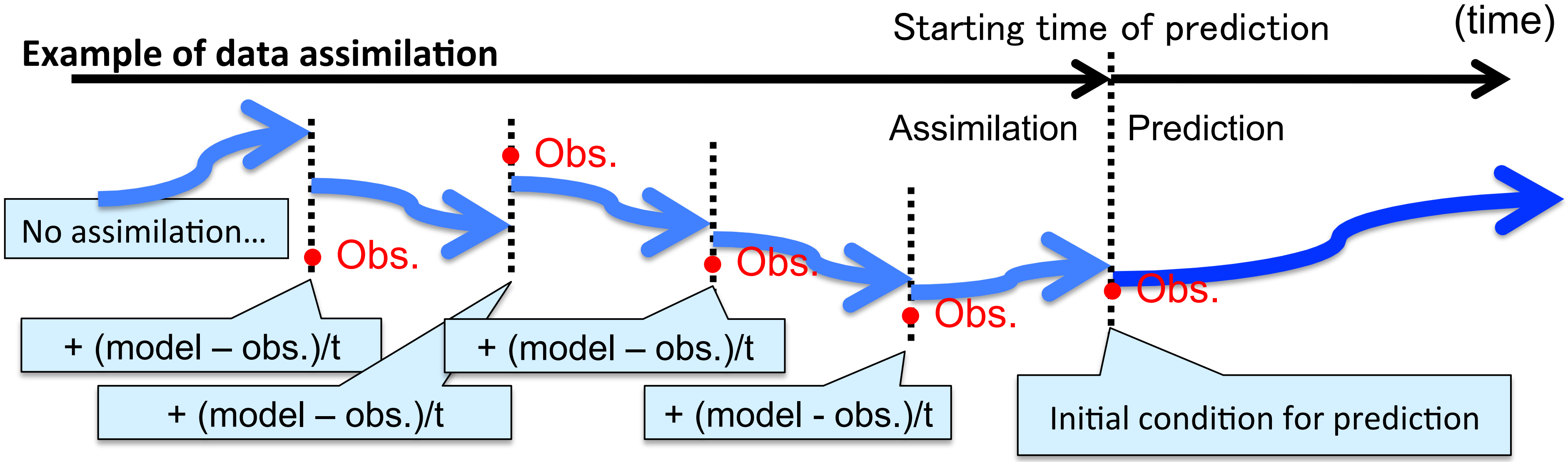
Fluctuations on decadal (10-20years) timescales



How to define initial conditions (initialization)…

- **Observed values are unsuitable as they are.**
  - Not always, not everywhere, not every variable
  - Not satisfying general principles (i.e., incompatible with climate model)

- **Value: Data assimilation** (nudging, optimal interpolation, 3d-var, 4d-var, Kalman filter/smoother,…)
  - Close to observed value
  - Almost satisfying general principles in model
- **Ensembles: Initial perturbation** (singular vector, breeding of growing modes, …)
  - Assimilated values with slight differences

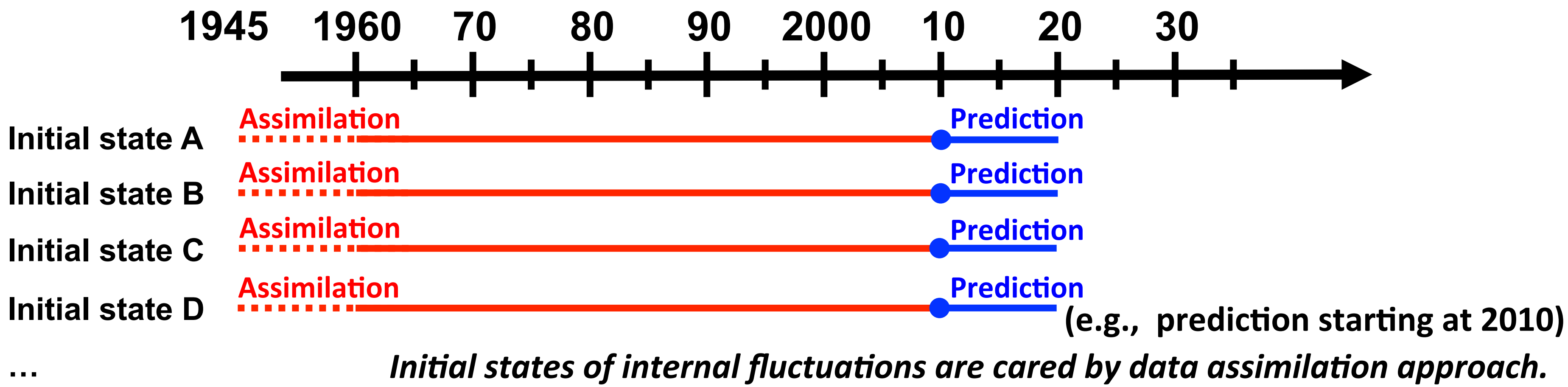


How to define initial conditions (initialization)…

- **Observed values are unsuitable as they are.**
  - Not always, not everywhere, not every variable
  - Not satisfying general principles (i.e., incompatible with climate model)

- **Value: Data assimilation** (nudging, optimal interpolation, 3d-var, 4d-var, Kalman filter/smoother,…)
  - Close to observed value
  - Almost satisfying general principles in model
- **Ensembles: Initial perturbation** (singular vector, breeding of growing modes, …)
  - Assimilated values with slight differences

Example of generating ensembles

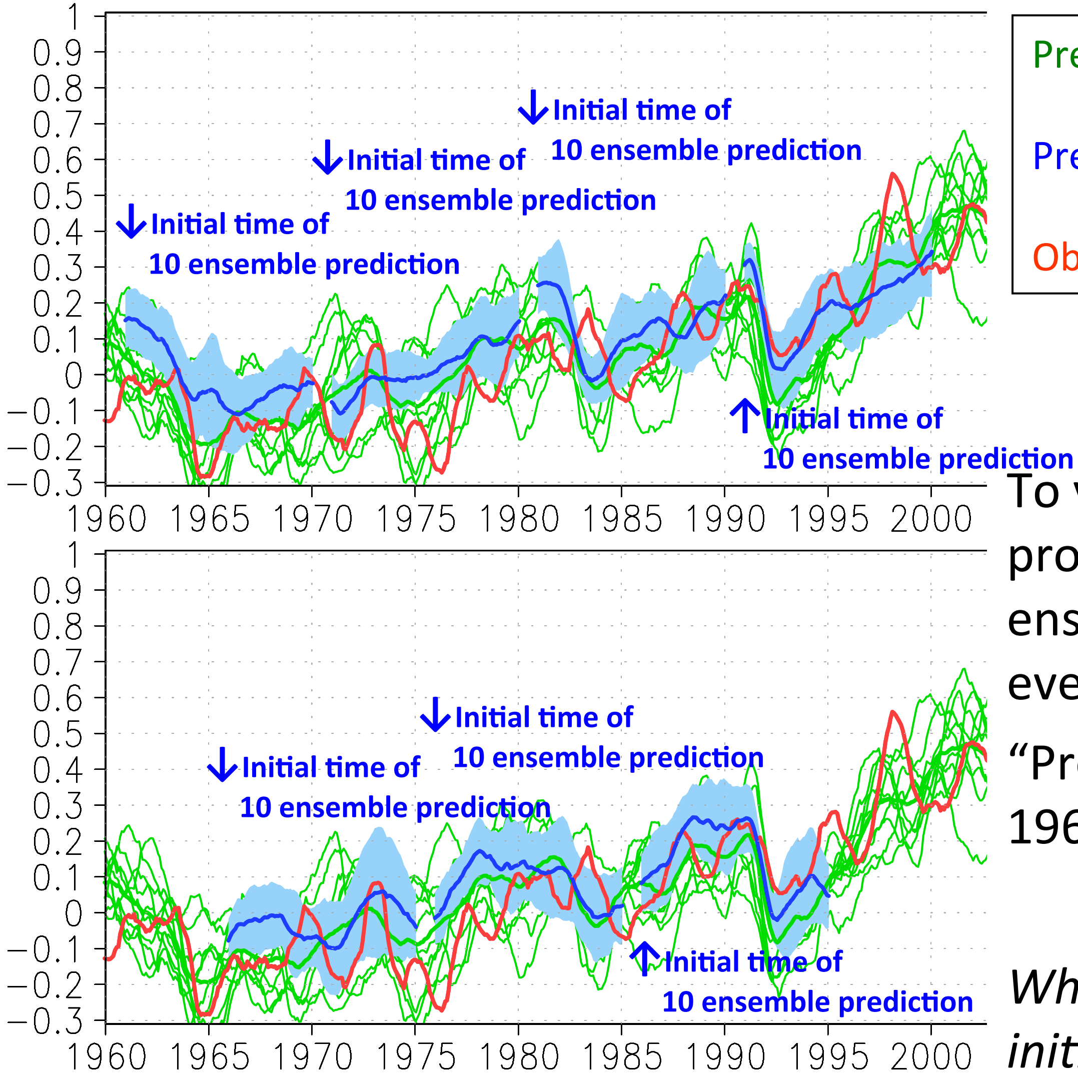


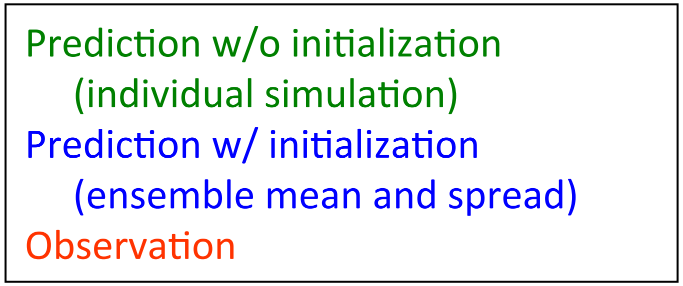
Initial states of internal fluctuations are cared by data assimilation approach.

Mochizuki et al. (2010, PNAS)

Sets of ensembles of initialized "prediction"

Global-mean surface air temperature anomaly (degC)





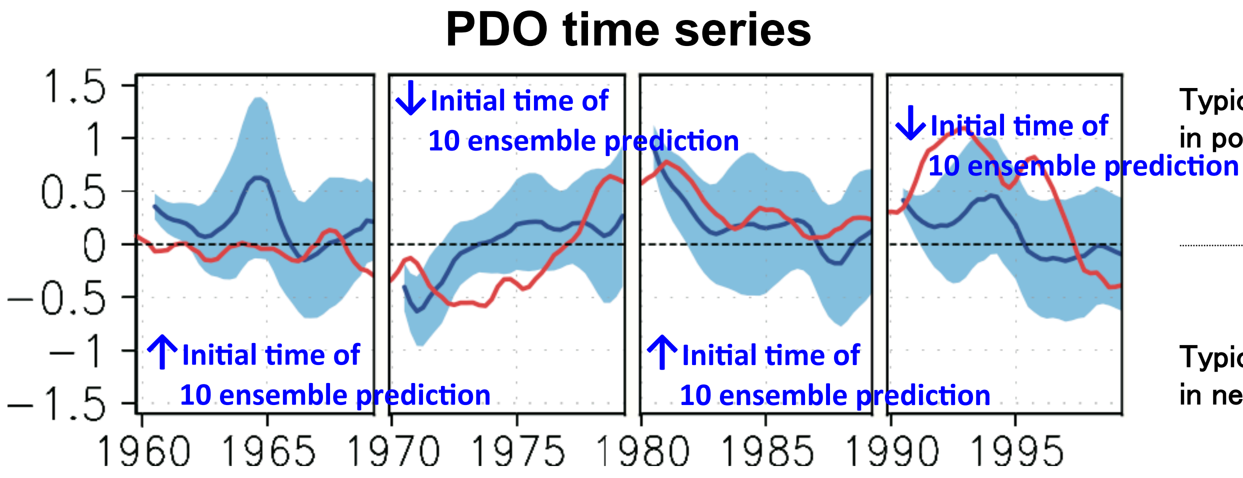
To validate prediction skill, in IPCC protocol, we perform sets of 10 ensembles of 10-yr-long "prediction" every five years:

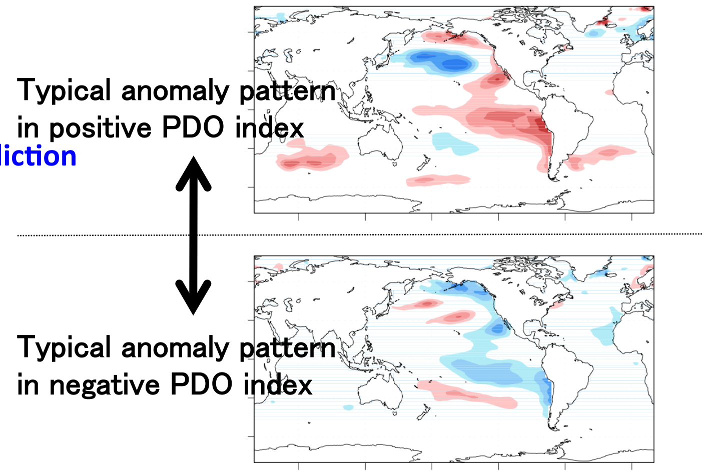
"Predictions" start at January of 1961, 1966, 1971, …, 1991.

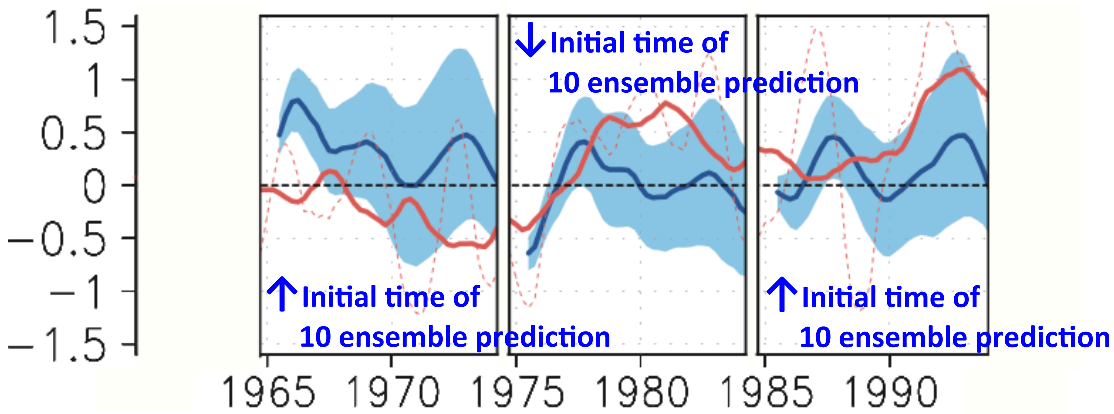
*When focusing on **global-mean state**, initialization has little impact on prediction…*

Mochizuki et al. (2010, PNAS)

Sets of ensembles of initialized prediction







Prediction w/ initialization
(ensemble mean and spread)
Observation

Prediction w/o initialization is nearly zero, since we plot deviations from global warming signal.

*When focusing on **internal fluctuations**, initialization has a large impact on prediction.*

PDO index (i.e., projection onto the modeled EOF1 of the North Pacific VAT300) is obtained by an EOF analysis to internal variations of the model, that are defined using a signal-to-noise maximizing EOF of 10-ensemble 20C3M simulations.

Mochizuki et al. (2010, PNAS)

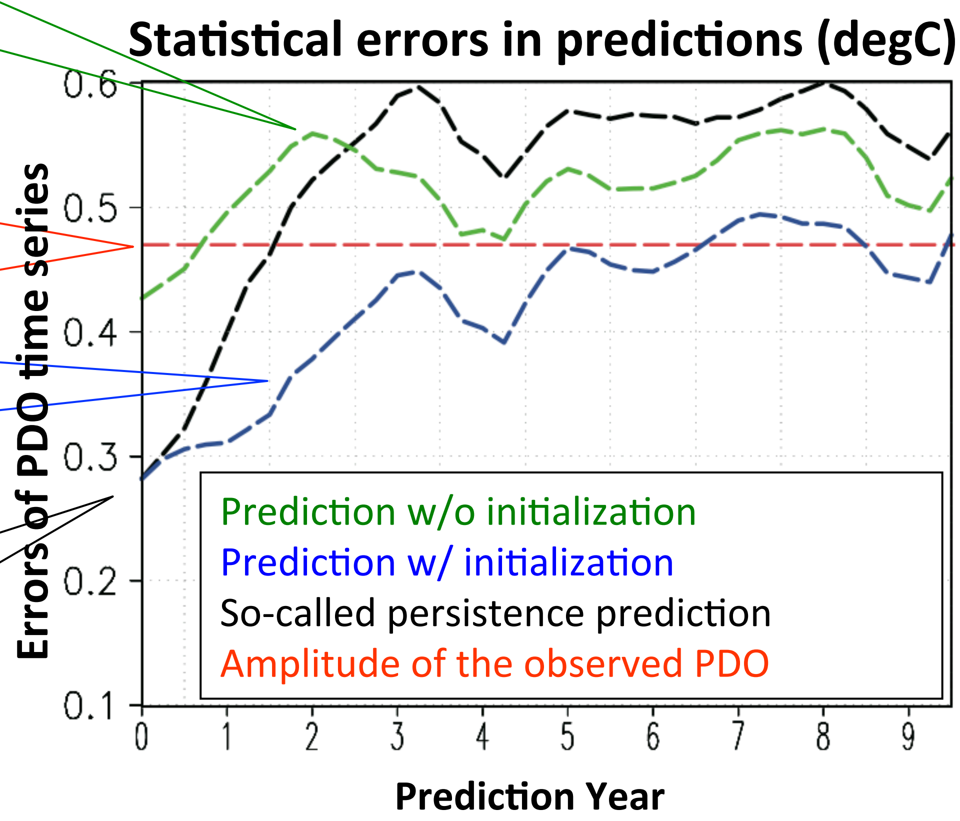
Sets of ensembles of initialized prediction

Prediction w/o initialization always represents about 0.5degC errors which is the same as the amplitude of the observed PDO.

On decadal timescales, uncertainty in prediction w/o initialization is primarily realized by the PDO (internal fluctuation).

Errors in prediction w/ initialization is smaller than the amplitude of the observed PDO during 5-6 years.

If keeping an initial condition as it is (i.e., so-called persistence prediction), errors rapidly grow to insufficient levels.



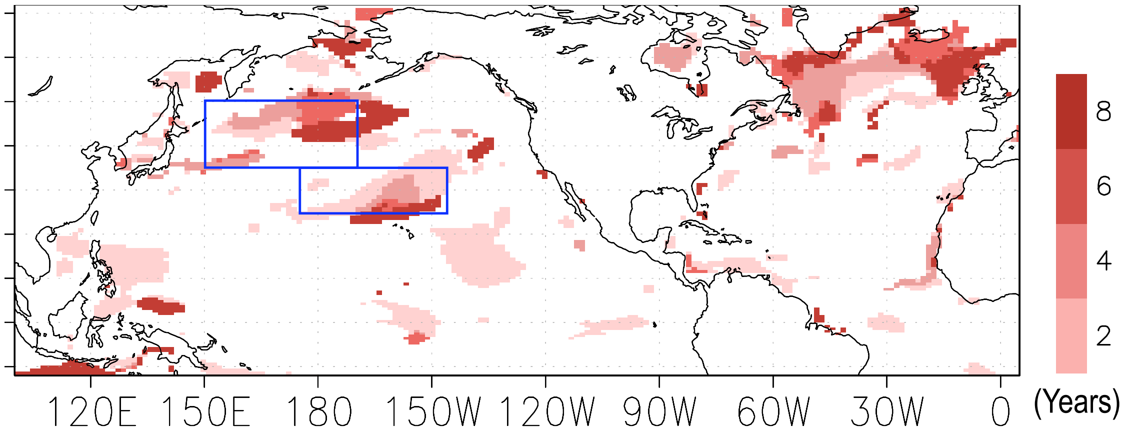
*When focusing on **internal fluctuations**, initialization has a large impact on prediction.*

PDO index (i.e., projection onto the modeled EOF1 of the North Pacific VAT300) is obtained by an EOF analysis to internal variations of the model, that are defined using a signal-to-noise maximizing EOF of 10-ensemble 20C3M simulations.

Mochizuki et al. (2010, PNAS)

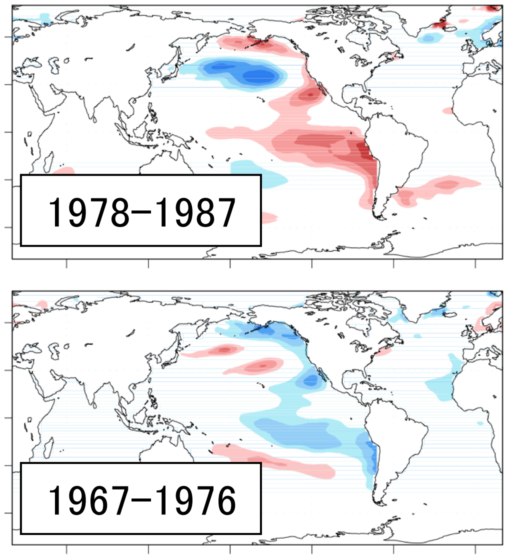
Predictive areas due to initialization

Areas where errors are significantly reduced in specific-year-long predictions



Areas where errors are significantly reduced
in 2, 4, 6, and 8 -year-long predictions
are found over …

- North Pacific: Pacific Decadal Oscillation (PDO)
- North Atlantic: Atlantic Multi-decadal Oscillation (AMO)



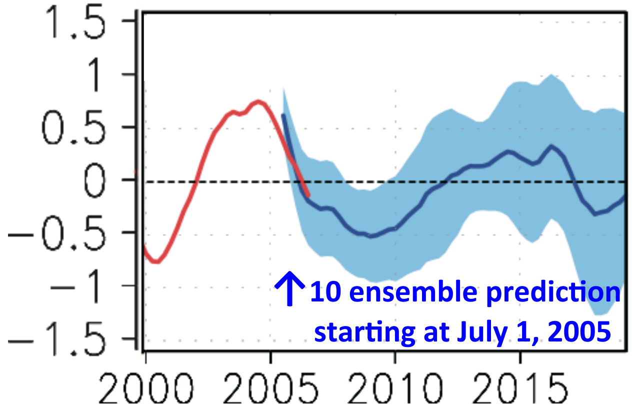
Remember!

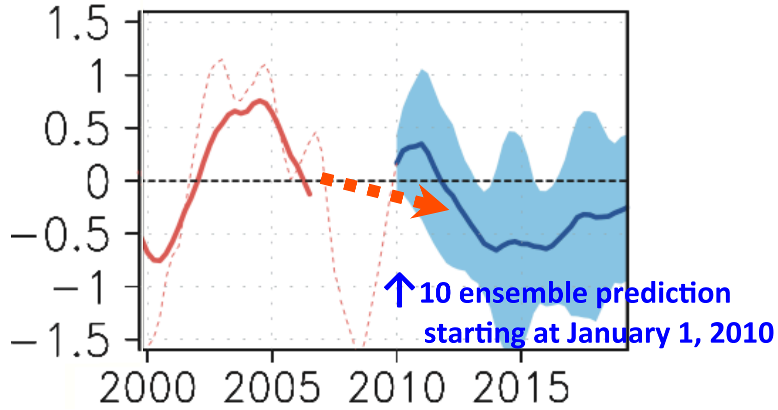
Predictive areas correspond to the regions where the PDO signals are observed strongest.

Predictable regions for 5-yr mean VAT300 (vertically averaged ocean temperature upper 300m) at specific hindcast years.
(Anomaly Correlation Coefficient > 90% significance levels)

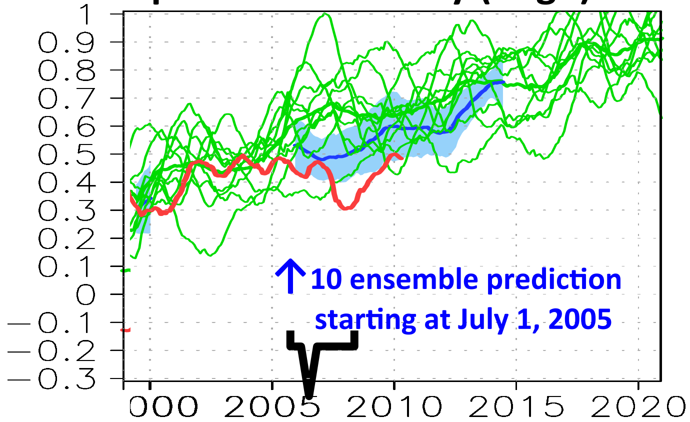
Applying to future climate prediction (2 examples)

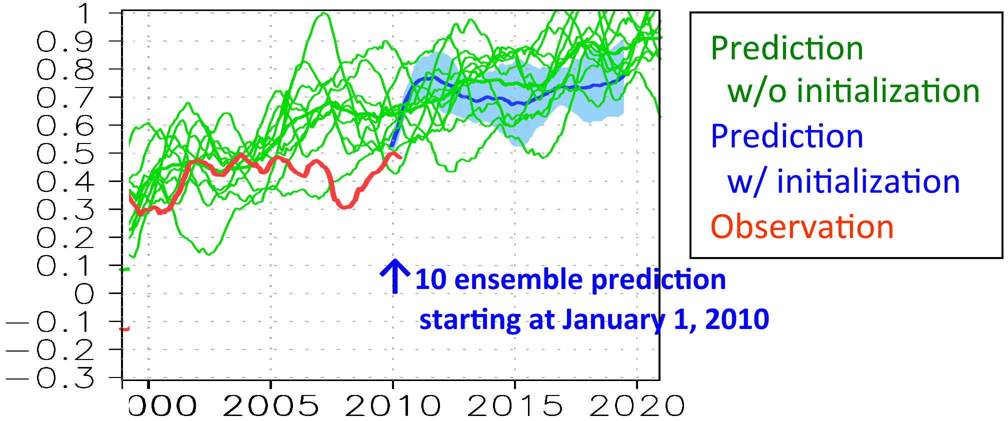
PDO time series



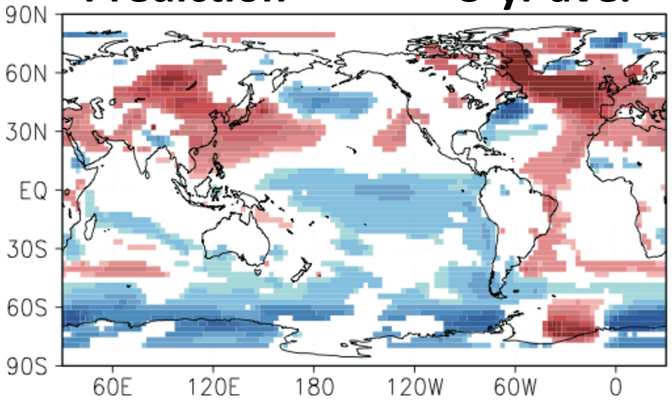


Global mean temperature anomaly (degC)

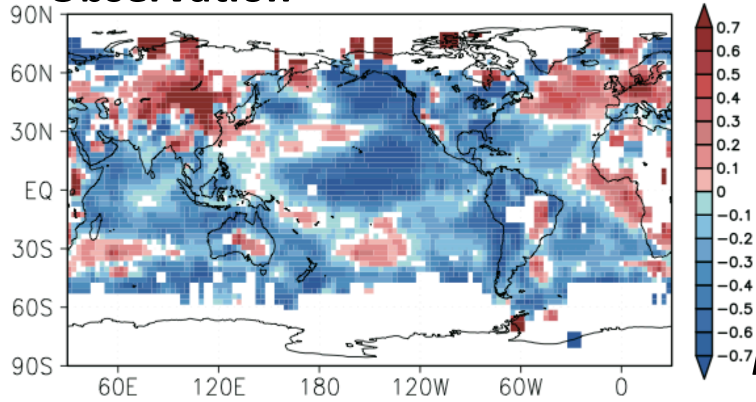




"Prediction" **3-yr ave.**



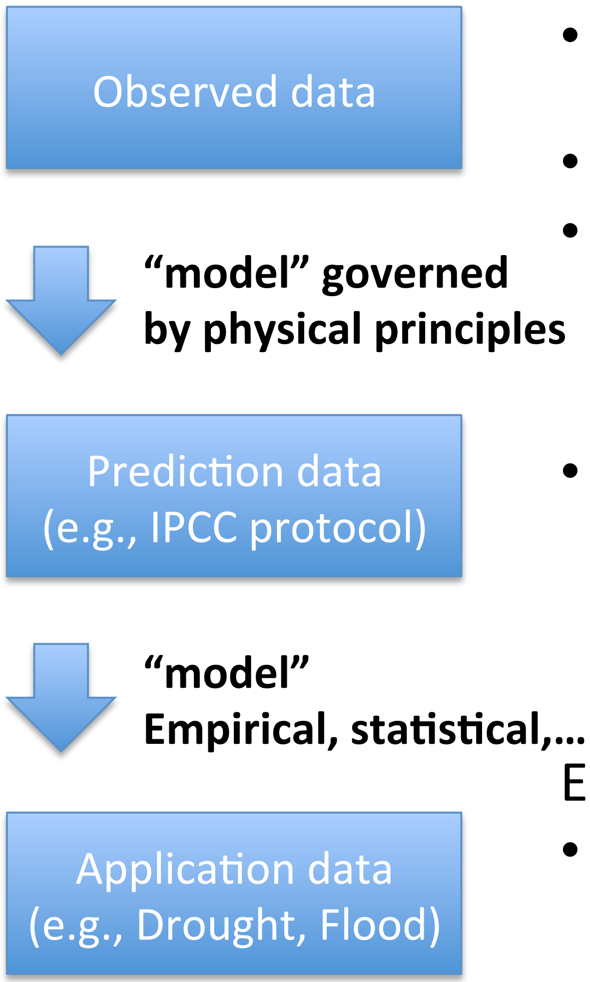
Observation



Predicted and observed fluctuations from global warming temperature change during 2006-08 (degC).

Mochizuki et al. (2010, PNAS)

Summary



- Climate "model" is generally governed by general principles.
- Climate "prediction" is basically **deterministic**.
- In a practical sense, we need implicit (i.e., **probabilistic / stochastic**) calculations to take into account contributions from small/short timescale phenomena.
- Rather than stochastic parameterization / physics, we use simpler **ensemble approach** to estimate uncertainty due to probabilistic / stochastic approximation.

Ensembles of IPCC-AR5 global warming simulations

- Long-term (centurial) prediction
  - Models / Parameterizations (≠ values of parameters)
- Near-term (decadal) prediction
  - Initial conditions (data assimilation)